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A SCENARIO FOR THE CONTAINMENT FAILURE OF BANEBERRY.(U)
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A SCENARIO FOR THE CONTAINMENT FAILURE OF BANEBERRY

Systems, Science and Software
P.O. Box 1620
La Jolla, California 92038

31 October 1975

Topical Report for Period 1 October 1974—31 October 1975

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A ground motion calculation for the Baneberry nuclear event is described here. A scenario is presented which indicates that the containment failure was due to the lack of a "mystical, magical membrane" around the Baneberry cavity. This membrane failed to form due to the negligible yield strength of the working point material which was over 50% montmorillonite clay.

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NOTE ADDED DECEMBER 1976

This work was done early in 1975, and this report was written in the summer of that year. Because of the general sensitivity of the subject, the report received only very limited distribution to interested ERDA representatives at that time. In fact, we were asked to withhold further distribution until additional calculations were completed and a more mature understanding of the influence of material strength on residual stress in layered media was obtained.

Most of the requested additional calculations have been finished, and many of the results have been presented to an Earth Motion Calculator's meeting held in La Jolla on May 4, 1976. Since the multidimensional calculations requested at that time have now been done and reported by LLL at the 66th CEP meeting, it seems appropriate, for archival reasons at least, to distribute the earlier report.

One minor change has been made in this document; namely, Reference 12 has been changed to a more complete and up-to-date presentation of the influence of material properties on residual stress and cavity radius. As mentioned above, additional and better calculations of the sort reported here have been completed, and a few more are to be done. An extended version of this report will be distributed in due course.

1. INTRODUCTION

This report discusses a recent study at Systems, Science and Software of Baneberry, an underground nuclear event detonated in Yucca Flat in December 1970. Baneberry failed to contain and therefore has been studied in great detail. However, a conclusive answer to the question of why Baneberry vented is still not available.

The Baneberry working point was located in an alluvial soil containing large concentrations of montmorillonite clay. A layer of alluvial material having high sonic velocities was directly above the working point while a paleozoic escarpment was located below and on one side of the working point. Postshot calculations by Crowley and Cherry (1971) looked into the effect of the high sonic velocity layer while Cherry, et al. (1974), discussed the effect of the escarpment. The general consensus of these studies, as I understand them, is that the containment failure of Baneberry is attributed to the high water content at the working point due to saturated clay, which resulted in extremely high coupling, and to the large impedance contrasts near the working point, which resulted in enhanced tension failure caused by the nonspherical ground motion compared with other events in Yucca Flat.

Since Baneberry remains of great interest today, a near field ground motion calculation of the event was made using the one-dimensional Lagrangian code, SKIPPER, incorporating the most recent geological and material properties data available. The results were compared with similar calculations for a Yucca Flat dry tuff, described in Bache, et al. (1974), and for a Rainier Mesa saturated tuff event (Husky Ace), described in Rimer, et al (1974). A scenario is presented which indicates that the containment failure of Baneberry may be due to an absence of significant compressive residual stresses around the Baneberry cavity. Residual stresses, due to nonuniform plastic loading of the rock, are observed in

most near field calculations at S^3 [see Rimer (1976)] and reach their final magnitudes at approximately the time the cavity attains its full growth. These residual stresses make the cavity produced by a nuclear explosion a relatively strong structure which contains gases very well. In the absence of this so-called "mystical magical membrane," tensile hydrofracturing is believed to have taken place, leading to venting of the cavity gases.

The plan of this report is to detail in Section 2 the geological and material properties data and modeling which were used in the calculations mentioned above. Section 3 discusses the results of these calculations. The conclusions of this report are summarized in Section 4.

2. MATERIAL PROPERTIES

The Baneberry device was emplaced at a depth of 912 ft in hole U8d on the far west side of Yucca Flat. A 1971 postshot analysis described the working point as fully saturated with an abnormally high water content for a WP located at least 900 ft above the water table due to the presence of large amounts of clay (montmorillonite) at this depth. This would be expected to give greater than normal ground shock motion when compared to other events in Yucca Flat. The seismic yield of Baneberry has in fact been estimated postshot (1971) at about three times the device yield of the event, while the measured surface motion was far greater than anticipated. The rock above the WP failed to contain the cavity gases which began to vent to the surface 3.5 minutes after detonation.

One-dimensional calculations were made postshot by Crowley and Cherry (1971) to study the effect of a high sonic velocity layer of saturated rock above the working point. Two calculations were made, one for a normal site, modeled as highly porous, dry alluvium, and another in which 230 ft of the alluvium directly around the WP was replaced by the high velocity layer. The

calculations indicated that the high velocity layer results in the same surface spall velocity for Baneberry yield as a blast of five times the yield in a normal site.

The one-dimensional calculation of Baneberry presented in this report utilizes geologic and material properties data not available in 1971 and also continues the calculation to later times (a few seconds) in order to examine the residual stresses around the cavity.

Preshot material properties data were based largely on a north-south line of satellite holes drilled for Discuss Thrower event emplaced in U8a, 1500 ft north of U8d augmented with some cuttings samples from U8d itself. The material around the Baneberry WP was determined to be undisturbed Ammonia Tanks tuff. Stephens, et al. (1971), have studied an altered tuff from the 1114-ft level of hole Ue8f, approximately 600 ft east of U8d. From a limited amount of sample, described as Ammonia Tanks tuff, they obtained both pressure-volume data to 30 kbar and a failure surface.

A new exploratory hole, U8ei, 360 ft south of U8d, was drilled in September 1973 in order to obtain a better description of the geology and material properties appropriate to Baneberry. The U. S. Geological Survey has restudied the cuttings samples in U8d and, because of the better quality of samples in Ue8i, suggests that the WP may be in colluvium rather than Ammonia Tanks tuff. Based on Ue8i samples, Ramspott (1975) has described the working point as being in a layer of over 50% montmorillonite rock. The water content in this saturated layer may be as much as 25% by weight. A higher overburden density than usual for Yucca Flat was reported. This would lead to a higher initial postshot cavity pressure. Ramspott has also mapped the approximate clay content of the rock layers about the working point. In the immediate vicinity, there is some justification based on clay content for modeling these layers as spherical.

From the above information, which is often conflicting, a consistent set of material properties data was chosen as initial conditions for a one-dimensional calculation of Baneberry using the Lagrangian SKIPPER code. The initial conditions consisted of a one-zone spherical cavity source containing the device energy at zero time and three spherical layers representing, respectively, the high clay content working point layer (50 ft thick), the high source velocity layer (120 ft thick), and an alluvial layer extending to the surface. This modeling should be considered applicable only to a vertical section through the working point to the surface. No attempt is made to treat the paleozoic escarpment. With the exception of the cavity source, all layers are modeled using the Tillotson equation of state, the p-α porous crushup model, and the parabolic failure surface described in the Appendix of this report. Table A-1 of the Appendix lists the material properties data used in the calculation.

For the working point layer (material 1), the pressure-volume curve was based on P-V data from Stephens, et al. (1971), while the yield strength was considered negligible due to the clay content. This is believed justified since the emplacement hole repeatedly caved in during drilling. This material was considered fully saturated. The alluvium layer (material 3) was based on equation of state data for Sedan alluvium obtained from C. Hastings. Air-filled porosity was computed to force these data to correspond to measured density for Baneberry alluvium. The high sound speed layer (material 2) was judged to have one-half the yield strength of the alluvium and to be more saturated due to its clay content (greater than 20%). An overburden pressure of 60 bars was included in the modeling.

The cavity source region was chosen to be initially large enough to just melt 70 metric tons of rock for each kiloton of device yield. The cavity pressure is given by an ideal gas law where gamma is a function of specific volume

($\gamma = 1.03 + 0.9/\sqrt{V}$). This expression for γ was obtained for tuff modeled as silicon dioxide from the Oracle Chemical Equilibrium Code adapted at S^3 from the Tiger Code discussed by Cowperthwaite and Zwisler (1971). This code uses the JCZ3 gas equation of state and the S3S solid equation of state of D. Laird (1975).

The results of this Baneberry calculation will be compared to results from calculations for an average Yucca Flat dry tuff described in Bache, et al. (1974), and for a saturated Rainier Mesa tuff (Husky Ace) described in Rimer, et al (1974). Since material properties information for Yucca Flat events is, in general, not extensive, an average dry tuff was modeled for the former calculation, based on L. Germain's (1974) summary of data for all dry tuffs. Using average values for bulk density, grain density, water content, porosity, and saturation, an equation of state was constructed using the Tabular Array of Mixture Equation of State (TAMEOS) scheme described in Riney, et al (1972). This scheme mixes grain density rock with water assuming pressure equilibrium between the mixture and its components in order to generate a Hugoniot and isentropes. The resulting pressures, energies, and specific volumes are rearranged into a fast table-lookup format. A crushup pressure and an elastic pressure limit, needed for the P-α porous crushup model, were calculated from empirical formulas available in Butkovitch (1973).

Sufficient material properties data are available to accurately model the almost fully saturated tuff found at Rainier Mesa. This calculation also utilized the TAMEOS scheme and the P-α model. A summary of the data used in the three calculations may be found in Table A-1 of the Appendix.

3. NUMERICAL RESULTS

Results from a spherical one-dimensional Baneberry calculation were compared with earlier results from calculations for a Rainier Mesa saturated tuff

and a Yucca Flat dry tuff. Peak velocity versus range has been plotted in Fig. 1 as a measure of the ground shock coupling of the three events. Note that the Baneberry free surface is not included in the calculation. All curves are scaled to the Baneberry yield. Over almost the entire range plotted, Baneberry peak velocity is intermediate between Rainier Mesa and Yucca Flat. However, Baneberry is seen to couple even higher than Rainier Mesa in the first layer ($r < 1524$ cm) containing large amounts of saturated clay. The agreement (shown in Table 1) between the Baneberry calculation and experimental measurements obtained from Crowley and Cherry (1971) is excellent.

Table 1. Comparison between Baneberry Data and Calculations

Station Location (meters)	Peak Velocity (meters/sec)	
	Data	Calculation
130	12.63	12.5
135	10.47	11.0

Peak radial stress vs range is plotted in Fig. 2 for the same three calculations. As in Fig. 1, Rainier Mesa saturated tuff plots higher than Baneberry except in the first layer of highly saturated clay. Baneberry couples much higher in peak stress than Yucca Flat dry tuff in the first two layers. However, in the alluvium layer ($r > 5180$ cm), the Baneberry calculation shows lower peak radial stresses than the dry tuff at the same range. This result follows from the yield strengths chosen for the two materials.

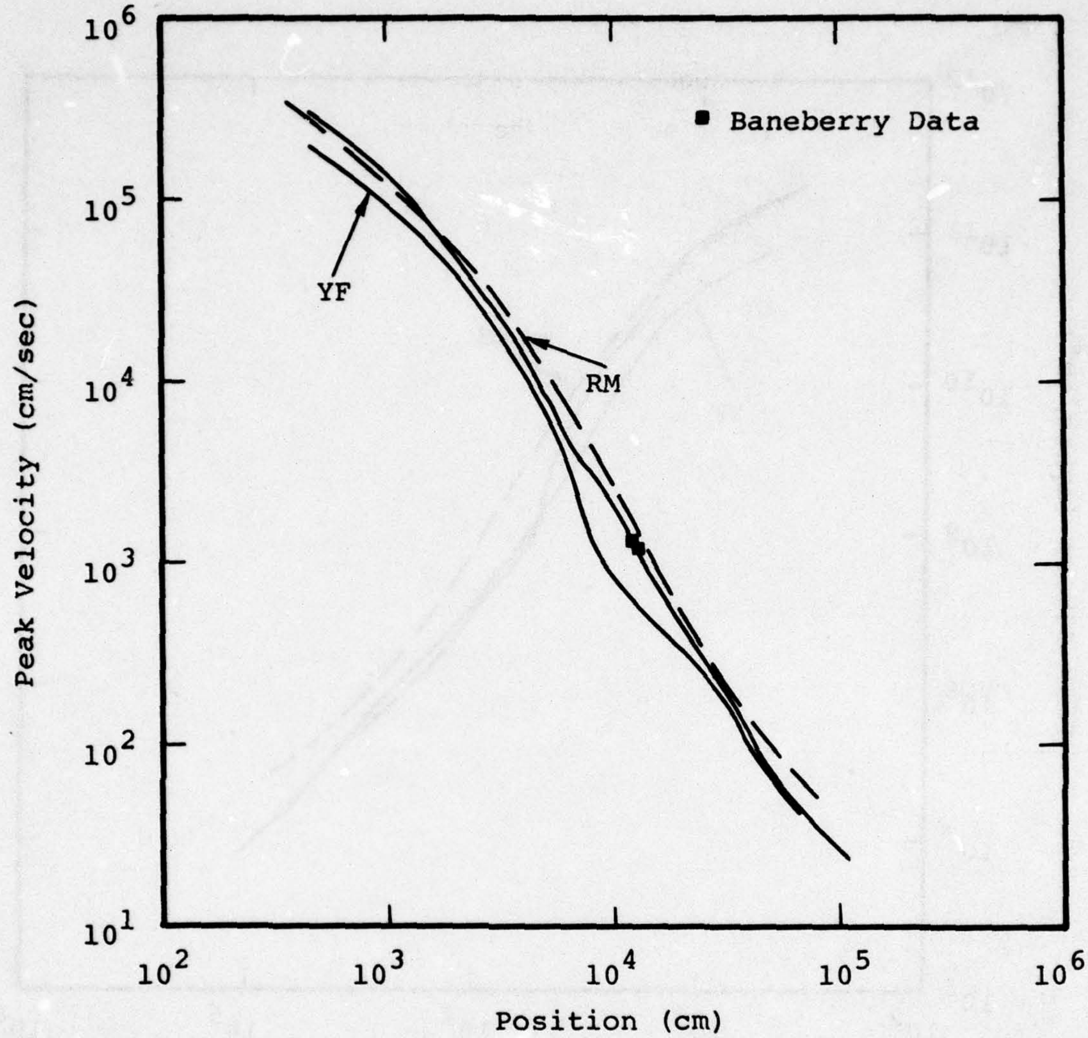

Figure 1 Peak velocity versus range for the Baneberry, Rainier Mesa and Yucca Flat calculations.

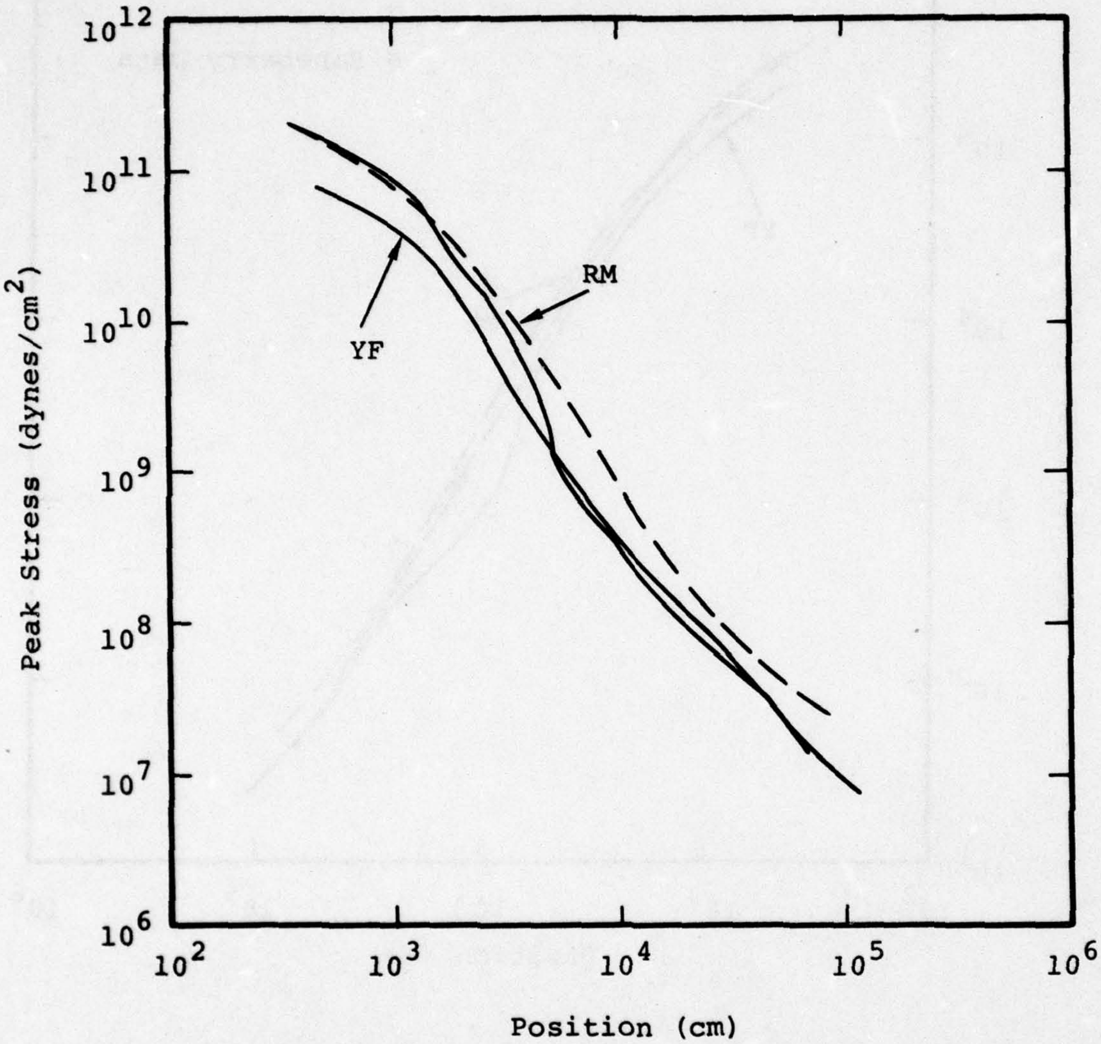

Figure 2 · Peak stress versus range for the Baneberry, Rainier Mesa and Yucca Flat calculations.

Figures 1 and 2 indicate much stronger near source coupling (in the saturated clay and high sonic velocity layers) from the Baneberry event than from a standard Yucca Flat shot. This result agrees with previous analysis of Baneberry. However, Baneberry did not couple as strongly as events on Rainier Mesa which were completely contained.

Near source data, such as in Figs. 1 and 2 give little insight into coupling at teleseismic distances. J. Savino (1975) of S^3 has analyzed teleseismic data from Rainier Mesa and Yucca Flat and concludes that body wave magnitudes from Baneberry (a shot located above the water table) were a factor of 5 greater than for other Yucca Flat shots above the water table, and a factor of 2 greater than Yucca Flat shots below the water table. This must be due to the saturated clay below and at the working point. However, it should be noted that Rainier Mesa shots give body wave magnitudes comparable to Baneberry.

It is proposed here that Baneberry vented due to the absence of an effective compressive residual stress field. Significant residual stresses are observed by Rimer (1976) for most of the calculations reported. Figure 3 shows the compressive residual stress field around the cavity for the Rainier Mesa calculation discussed above. An overburden pressure of 56 bars must be added to the stress shown. These stresses tend to resist the cavity pressure and thus contain the cavity gases. Duff, et al. (1975), have reported that for a residual stress field comparable to the Rainier Mesa calculations, cavity pressures almost three times overburden can be developed before any possibility of tensile failure is to be expected. Thus, residual stresses result in a strong cavity structure, acting to prevent tensile hydrofracturing.

No comparable residual stress field is seen in the Baneberry calculation. In fact, in order to find any residual stresses of significant magnitudes in Baneberry, one must look at the third (alluvium) layer. Figure 4 shows the radial

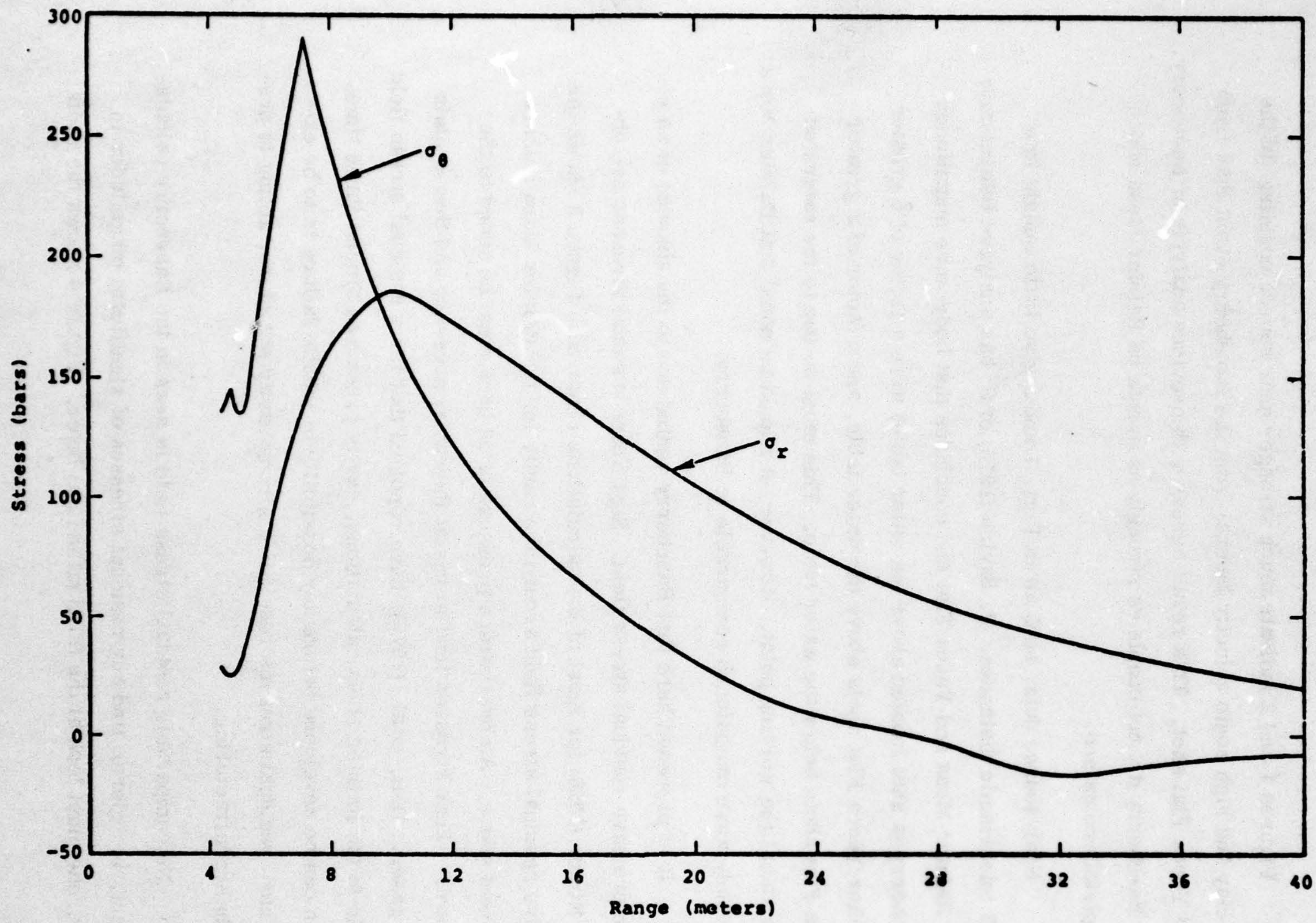

Figure 3 Radial and tangential residual stress versus final position for Rainier Mesa material properties.

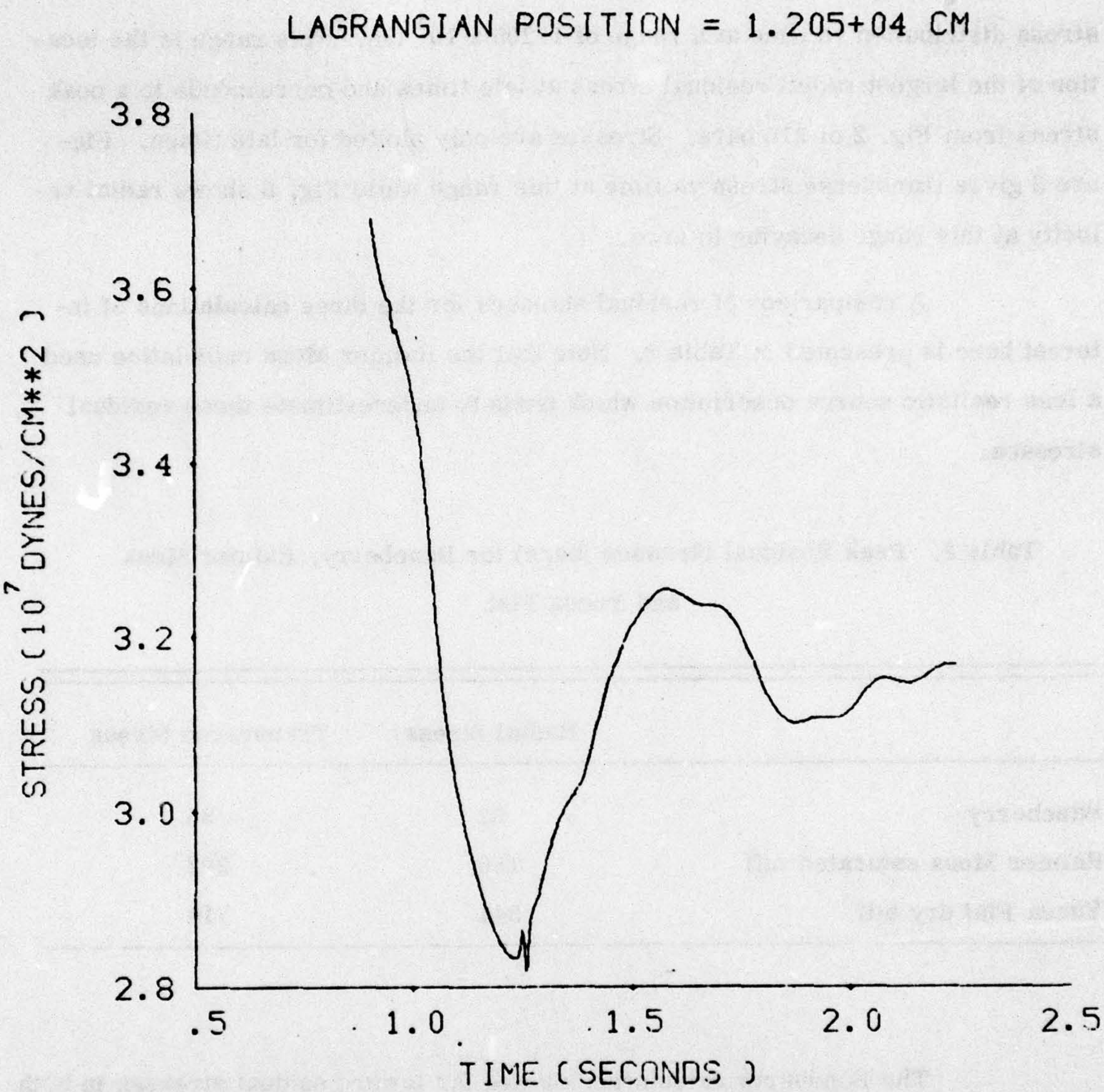

Figure 4 Radial stress versus time for Baneberry.

stress distribution vs time at a range of 1.205×10^4 cm. This range is the location of the largest radial residual stress at late times and corresponds to a peak stress from Fig. 2 of 215 bars. Stresses are only plotted for late times. Figure 5 gives transverse stress vs time at this range while Fig. 6 shows radial velocity at this range decaying to zero.

A comparison of residual stresses for the three calculations of interest here is presented in Table 2. Note that the Rainier Mesa calculation used a less realistic source description which tends to underestimate these residual stresses.

Table 2. Peak Residual Stresses (bars) for Baneberry, Rainier Mesa and Yucca Flat

	Radial Stress	Transverse Stress
Baneberry	32	35
Rainier Mesa saturated tuff	180	292
Yucca Flat dry tuff	344	714

The Baneberry calculation showed far lower residual stresses in both the radial and transverse directions. This is not surprising since the Baneberry working point layer is believed to have negligible yield strength due to the high saturated clay content as evidenced by many caveins during drilling. Rimer (1976) has shown the magnitudes of residual stresses to be proportional to yield strength.

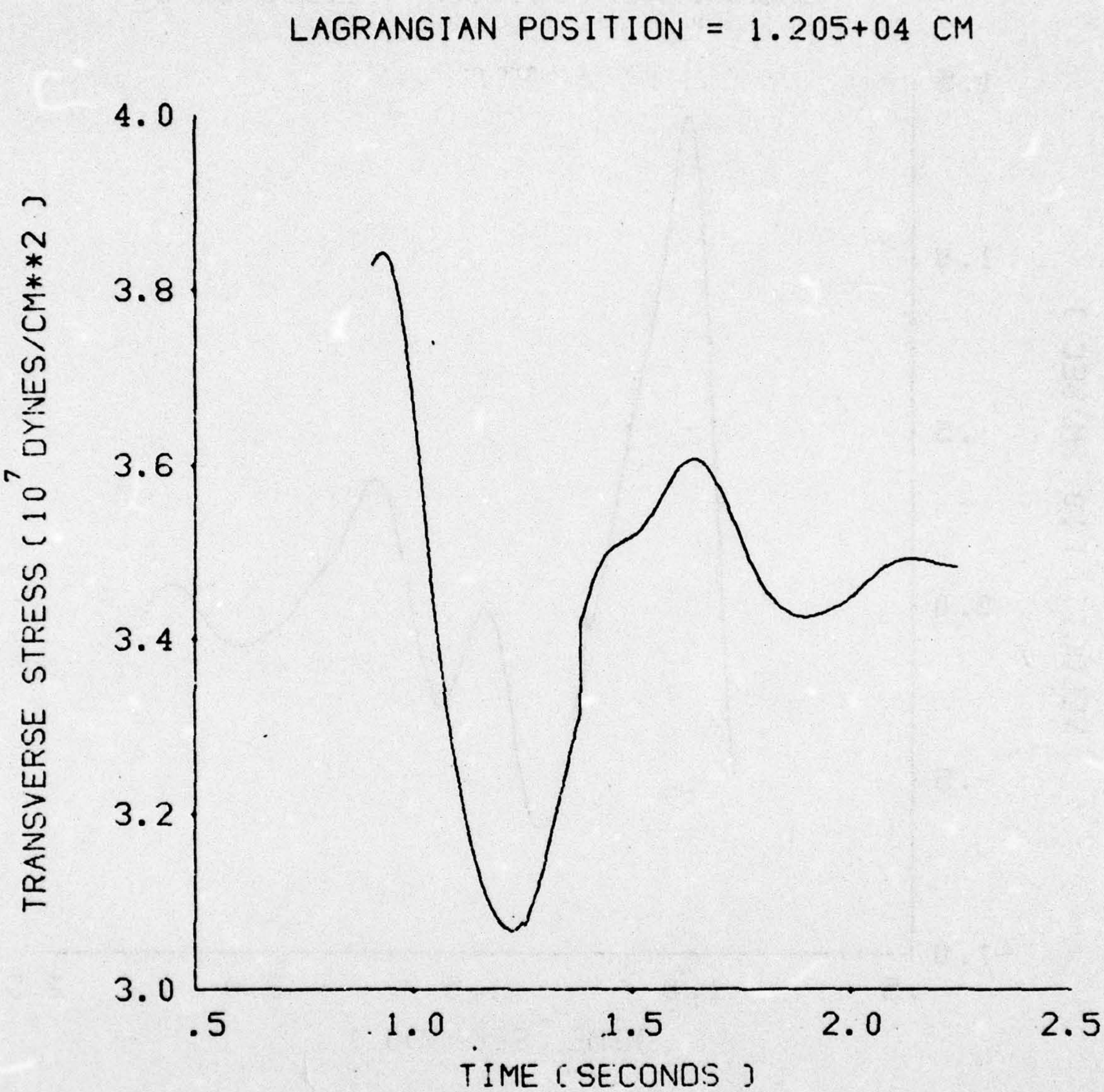

Figure 5 Transverse stress versus time for Baneberry.

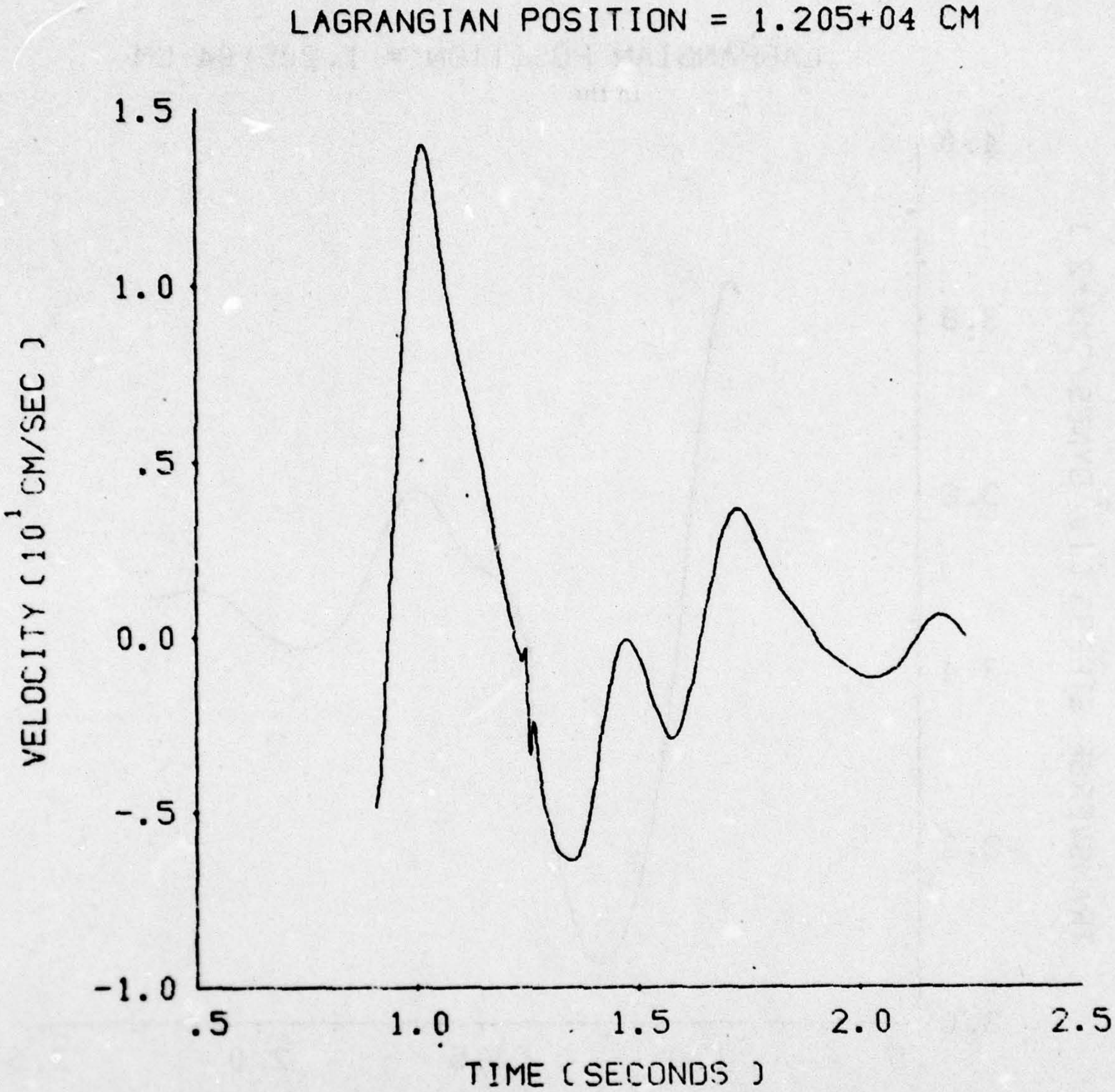

Figure 6 Radial velocity versus time for Baneberry.

The negligible residual stresses seen for the Baneberry calculation can hardly be expected to contain the cavity gases. In fact, in light of the results for the Rainier Mesa calculations, in the absence of a significant residual field at late times, tensile hydrofracturing would be likely. No evidence is presented here showing how far from the source fracturing may extend or whether it would indeed extend to the surface. This is a complex question involving the condensible flow of steam in a growing crack. However, the paleozoic escarpment probably was incidental to the venting, but it may have influenced the direction and propagation of the crack.

4. CONCLUSIONS

The calculations presented here do, in fact, show, as reported by others, that Baneberry does couple higher than other shots in Yucca Flat, due to the saturated clay about the working point and the high sonic velocity above the working point. However, this coupling is lower than for Rainier Mesa shots which consistently are contained. Therefore, it is concluded that the higher coupling was probably not the cause of the containment failure of Baneberry.

A definitive two-dimensional calculation of Baneberry using the latest equation of state data has yet to be done. This calculation should be made and should incorporate the most sophisticated treatment of tension failure possible, such as the model now available at S^3. Such a calculation would address the question of whether the impedance mismatch at the high sonic velocity layer would greatly increase the likelihood of tension failure. It is possible that the tension failure induced by the impedance mismatch could destroy the residual stress membrane around the cavity.

In the absence of the two-dimensional calculation, the following scenario is presented as leading to the venting of cavity gases to the surface to late

times. The working point material was extremely noncompetent due to the saturated clay content, leading to numerous caveins during excavation. Therefore, this material would be expected to have a negligible yield strength. Since the magnitudes of the compressive residual stresses around the cavity are proportional to the yield strength, these stresses would be negligible for Baneberry. In fact, the Baneberry calculation showed them to be an order of magnitude lower than for a comparable Yucca event. Thus, no "mystical magical membrane" would be developed around the cavity. In the absence of this membrane tensile hydrofracturing would be likely to occur. If this fracturing was sufficiently great, venting would occur. The presence of the paleozoic escarpment is believed incidental to the venting, though it might have some influence on the location of the fissure.

In conclusion, the negligible yield strength of the working point material was the most significant factor in the containment failure of Baneberry. High water content, while enhancing ground shock coupling, was not a major factor. To insure a structurally strong cavity capable of containing the cavity gases, the working point should be located in a competent material with significant yield strength.

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APPENDIX

The Baneberry calculation models the rock using an equation of state of the form developed by Tillotson (1962) and fit at S^3 to available shock data for a number of geological materials. For compressed states $(\rho < \rho_0)$ and for cold expanded states $(\rho < \rho_0$ and $e < e_s)$, the pressure is given by

$$P_s = \left[a + \frac{b}{\frac{e}{e_0\eta^2} + 1} \right] e\rho + A\mu + B\mu^2 \quad .$$

For expanded states $(o < o_0)$ where $e > e_s'$, the pressure is given by

$$P_v = aeo + \left[\frac{be\rho}{\frac{e}{e_0\eta^2} + 1} + A\mu e^{-\beta\left(\frac{\rho_0}{\rho} - 1\right)} \right] e^{-\alpha\left(\frac{\rho_0}{\rho} - 1\right)^2} \quad .$$

The phase transition from liquid to vapor $(\rho < \rho_0$ and $e_s < e < e_s')$ is approximated as

$$P = \frac{1}{e_s' - e_s} \left[(e - e_s) P_v + (e_s' - e) P_s \right] .$$

Here

ρ = mass density

$\eta = \rho/\rho_0$

$\mu = \eta - 1$

e_s = specific internal energy as the material is brought to vaporization temperature

$e_s{}'$ = additional energy required to change the material from a liquid to a vapor state

Air-filled porosity ϕ_0 is included through the S^3 porous crushup model (p-γ model) in which the pressure of the porous material is described by

$$p = \frac{1}{\alpha}\,\bar{p}\left(\frac{V}{\alpha},\, e\right)$$

where

v = specific volume of porous material

e = specific internal energy of porous material

$\bar{p}$ = pressure obtained from equation of state

α = distension ratio defined by $\alpha = v/\bar{v} \geq 1$

where $\bar{v}$ is the specific volume of the material with zero air-filled voids.

The distension ratio is required to decrease from an initial value (at p = 0) down to 1.0 as the pressure increases to p_c, the pressure limit at which all air-filled porosity is irreversibly removed. The pressure limit for the reversible portion of the pore collapse, p_e, locates the boundary between two functions $\alpha(v)$, elastic and plastic, which together define the crush curve.

The material strength model used in SKIPPER requires that the principal stress be within the von Mises yield surface. For spherical geometry, this reduces to the condition that the magnitude of the deviatoric component of the stress in the radial direction not exceed 2/3 the yield strength. The yield function Y, considered to depend both on pressure and energy, for $e < e_m$ is given by

$$Y = \left[Y_0 + Y_m \frac{p}{p_m}\left(2 - \frac{p}{p_m}\right)\right]\left(1 - \frac{e}{e_m}\right) \qquad p < p_m$$

$$Y = (Y_0 + Y_m)\left(1 - \frac{e}{e_m}\right) \qquad p \geq p_m$$

where

Y_0 = yield strength at zero pressure

p_m = pressure at which the maximum stress difference under triaxial compression $(Y_0 + Y_m)$ is attained

e_m = energy of melting

For energies greater than e_m, no deviatoric stresses are permitted.

Table A-1 summarizes the equation of state parameters and elastic properties; sonic velocity (c_0), bulk modulus (k_0), and shear modulus (G), used in the calculations.

Table A-1. Material Properties for Baneberry, Yucca Flat Dry Tuff, and Rainier Mesa Saturated Tuff

Property	Baneberry			Yucca Flat	Rainier Mesa
	Material 1	Material 2	Material 3		
ρ_0 (gm/cm^3)	1.91	2.128	2.016	1.7	1.91
c_0 (km/sec)	1.607	2.086	1.606	2.13	2.34
G (kbar)	7	30	15	25.8	35.7
k_0 (kbar)	40	50	32	55	57.2
ϕ_0	0	0.05	0.10	0.1564	0.012
Y_m (kbar)	0	0.05	0.10	0.62	0.18
Y_0 (kbar)	0	0.007	0.007	0.12	0.055
P_m (kbar)	0	0.7	0.7	0.4	0.4
P_e (kbar)	-	0.07	0.07	0.18	0.05
P_c (kbar)	-	2.0	2.0	4.36	1.5
P_0 (kbar)	0.060	0.060	0.060	0.096	0.056
e_m (10^{10} erg/gm)	2.15	2.15	2.15	2.0	2.0
e_s (10^{10} erg/gm)	3.7	3.7	3.7	-	-
e_s' (10^{10} erg/gm)	17.5	17.5	17.5	-	-
e_0 (10^{10} erg/gm)	10	10	10	-	-
A (kbar)	40	79.3	79.3	-	-
B (kbar)	352	803	803	-	-
a	0.4	0.4	0.4	-	-
b	0.6	0.6	0.6	-	-
f_w	-	-	-	0.136	0.17
$\bar{\alpha}$	5	5	5	-	-
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